Characterization of a Si/SiC Fusion power module on an inverter/e-Drive testbench

H. Akabay, N. Gorte, K. Ezzeddine, Ch. Pannemann,
Infineon Technologies AG, Max-Planck-Str. 5, D-59581 Warstein

Abstract

The combination of silicon (Si) and silicon carbide (SiC) technologies offers significant cost and performance advantages. This study quantifies the efficiency of a Si/SiC based inverter system, highlighting its benefits in terms of reduced energy losses. The quantification is achieved using a laboratory inverter system with the Infineon HybridPACK™ Drive G2 Fusion power module combining both Si and SiC technologies. The evaluation is performed on a motor test bench consisting of two mechanically coupled 85 kW permanent magnet synchronous motors (IPMSM) at speeds of up to +/- 5500 rpm and torques of up to +/- 250 Nm. This range ensures that operating points in both the constant torque and field weakening regions of the motor are covered. The experimental results show that inverter efficiencies more than 98.8% were achieved. Finally, the measured data was used to generate efficiency maps and simulate WLTP profiles for the Si/SiC Fusion module, which are then compared to the Si and SiC standard modules. Similarly, the obtained results under WLTP show that the Fusion module ensures improved vehicle range as compared to the Si and SiC modules.

I. Introduction

The automotive industry is undergoing a transformative shift towards battery electric vehicles (BEVs) to meet global sustainability goals, necessitating advancements in power electronics. Central to this evolution is the development of efficient traction inverters, which are crucial for optimizing energy efficiency, power density, and overall vehicle performance. While silicon (Si)-based insulated gate bipolar transistors (IGBTs) have been the cornerstone of inverter technology due to their cost-effectiveness, they face limitations in efficiency and high-temperature operation. Conversely, silicon carbide (SiC) metal oxide semiconductor field-effect transistors (MOSFETs) offer superior efficiency and thermal capabilities but are hindered by high costs and limited availability.

To address these challenges, hybrid power modules that combine Si and SiC technologies have emerged as a promising solution. These modules aim to strike a balance between cost and performance by leveraging the cost-effectiveness of Si IGBTs and the superior efficiency of SiC MOSFETs. This study focuses on the Infineon HybridPACK™ Drive G2 Fusion power module, which integrates 30% SiC and 70% Si components, designed to achieve near-full SiC efficiency at a reduced cost.

The research evaluates the efficiency of this hybrid module under various operating conditions using a sophisticated test bench with two mechanically coupled 85 kW permanent magnet synchronous motors (IPMSMs). The results are compared with traditional Si IGBT and full SiC modules, demonstrating the hybrid module's exceptional efficiency, reaching over 98.8%. Additionally, simulations under the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) highlight the module's real-world benefits, showing a 2.9% increase in vehicle range compared to Si IGBTs.

This study underscores the significance of hybrid modules in enhancing inverter efficiency and vehicle performance, offering a viable solution for the automotive industry's transition to sustainable transportation. By bridging the gap between cost and performance, the Si/SiC Fusion technology not only supports current advancements but also paves the way for future developments in power electronics.

II. The Si/SiC Fusion Power Module: Advancing Efficiency and Reliability in Automotive Power Electronics

The Si/SiC Fusion Power Module represents a significant advancement in power electronics, particularly for automotive applications. By integrating SiC MOSFETs and Si IGBTs into a single module, it optimizes performance across a wide range of operating conditions. The use of a single gate driver board enables simplified control, allowing both components to operate in parallel with a single gate signal. This design not only enhances efficiency but also ensures ease of system management [1].

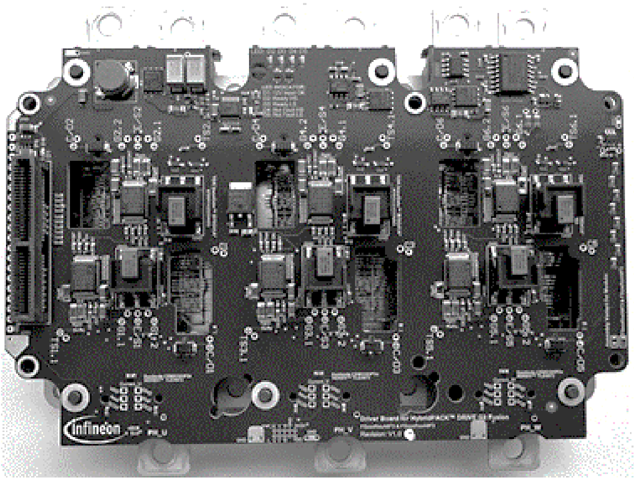


Figure 1 Fusion module with single gate driver board [1]

Under light load conditions, such as those around 150 A RMS, the SiC MOSFETs dominate operation, utilizing their fast-switching capabilities and low conduction losses to enhance efficiency. This results in a significant reduction in conduction losses, particularly in the critical 150 A RMS range, where efficiency is crucial for maximizing driving range. The near-ohmic behavior of the SiC MOSFETs contributes to this efficiency, avoiding the higher losses associated with the pn-junction drop of Si IGBTs.

At higher load conditions, such as during vehicle acceleration where currents can reach up to 750 A RMS, the Si IGBTs take on a more prominent role. This prevents the SiC MOSFETs from being overloaded, thus safeguarding against exceeding their current density limits. The Si IGBTs, with their higher current handling capability, ensure robust operation while maintaining cost-effectiveness by reducing the need for larger, more expensive SiC dies.

Analyzing the currents used during a classic CLTC-P/WLTP Class 3 cycle reveals that, for 75% of the operating time, these are less than 150 A RMS. Therefore, it can be said that, in classic driving mode, the vehicle is in a light-load condition and can utilize the advantages of the SiC MOSFET (see Figure 2). [2]

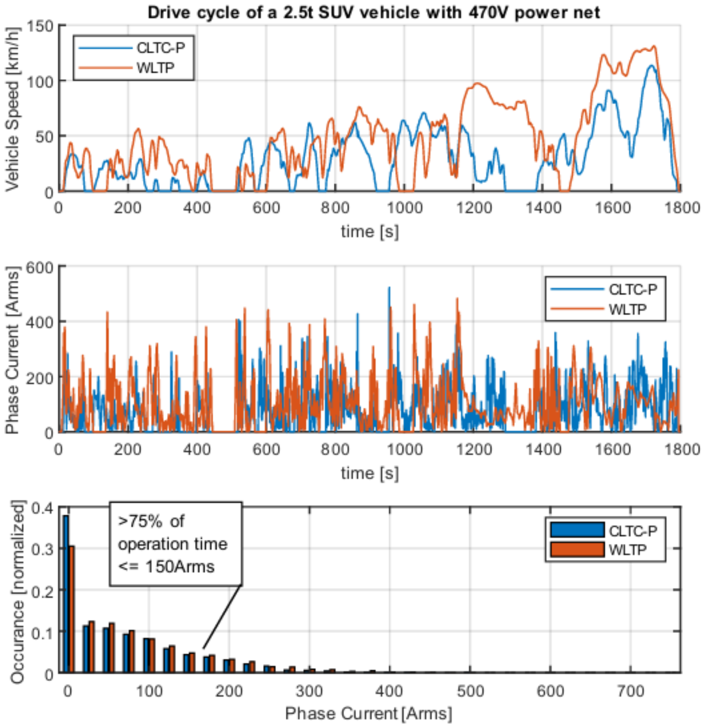


Figure 2 Drive cycles CLTC-P and WLTP class 3 [3]

The Fusion switch also incorporates advanced features for reliability and protection. A series resistor (Rs) of 1 kΩ protects the gate driver and on-die temperature sensors from transient current spikes. The module includes on-die temperature sensor diodes for precise thermal monitoring, which is crucial for maintaining optimal operation and preventing overheating. Additionally, the use of a common gate driver with dedicated turn-on (Rgon) and turn-off (Rgoff) paths, along with an additional Rgsoft(off) path for extreme conditions, ensures reliable and safe operation (see Figure 3).

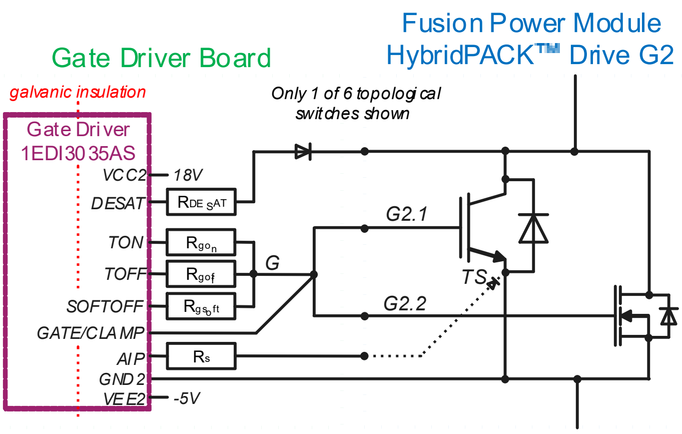


Figure 3 Si/SiC Fusion switch configuration with a single gate driver for simultaneous switching [3]

In rectification mode, the SiC MOSFETs share the current with Si diodes. The SiC MOSFETs dominate conduction up to 300 A, thereby reducing losses by over 75%. At higher currents, the Si diodes provide support to the MOSFETs, ensuring that the module achieves the necessary I^2t capability for fault conditions, such as active short circuits in motor windings. This dual operation optimizes performance and reliability across a wide range of operating conditions.

Table 1. Requirements for the utilization of chips for the efficient and safe operation of inverters [3]

Operating Mode	Chip Utilization		
	SiC MOSFET	Si IGBT	Si Diode
Light load (0.. 250A_{rms})	Full	**Minimum**	Minimum
Peak load turn-on (500..750A_{rms})	Full (1/3 of total current)	**Full (2/3 of total current)**	Medium to Full
Active Short Circuit	Full	Medium	Full
Short Circuit	Full	Full	n.a.

The Fusion switch's design not only optimizes efficiency and robustness but also enhances electromagnetic compatibility (EMC). By reducing switching noise, it minimizes the need for additional EMC measures, thereby contributing to a more compact and cost-effective system design.

In summary, the Fusion switch represents an innovative solution in power electronics, combining the strengths of SiC and Si technologies to achieve exceptional efficiency, reliability, and cost-effectiveness in automotive inverters. Its hybrid configuration ensures optimal performance across various load conditions, making it an ideal solution for modern electric vehicles [3].

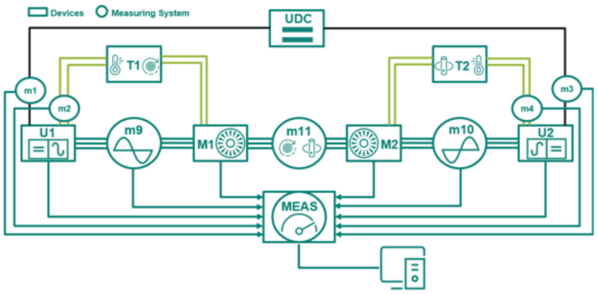
III. Efficiency Estimation of Automotive Power Modules

III. 1. Inverter/e-Drive test bench

To measure the efficiency of the Si/SiC Fusion Power Module under application-related conditions, it was integrated into the Inverter/e-Drive test bench. The test bench is a sophisticated experimental platform designed to evaluate the performance of power electronic inverters under realistic automotive operating conditions. It consists of two mechanically coupled permanent magnet synchronous machines (IPMSMs), sourced from the Volkswagen E-Golf (type EAQ270), each capable of delivering up to 85 kW of power, 270 Nm of torque, and operating speeds up to 12,000 rpm. One motor is configured for speed control, while the other is set up for torque control, enabling the assessment of the inverter's performance under diverse operating conditions.

The test bench features a common DC link, which acts as the central element for energy exchange between the systems, and a bidirectional DC source equipped with a regenerative electronic load. This setup facilitates four-quadrant operation, essential for simulating real-world automotive scenarios, including motoring and generating modes.

Controlled by a personal computer with dedicated software, the test bench employs a sinusoidal pulse-width modulation (SPWM) scheme for precise regulation of motor speed and torque. The system is equipped with high-precision sensors and a data acquisition system capable of measuring speed, torque, voltage, and current under application-relevant conditions. This comprehensive setup enables detailed evaluations of inverter performance, efficiency, and thermal behavior, making it a versatile tool for advancing power electronic technologies in automotive applications [4].



UDC	DC-Link	m1/m3	Measurement of DC currents / voltages Inverter 1 / Inverter 2
U1	Inverter 1 (speed controlled)	m2/m4	Measurement of speed and temperature of motor M1 / M2
U2	Inverter 2 (torque / current controlled)	m9/m10	Measurement of AC currents / voltages of motor M1 / M2
M1	Motor 1 (speed controlled)	m11	Measurement (speed / torque) of motor M1/M2)
M2	Motor 2 (torque / current controlled)	MEAS	Measuring system
T1/T2	Measurement (speed / temperature of motor M1 / M2)		

(a) (b)

Figure 4. Electric Motor Test Bench (a) structure and (b) different elements [4]

III. 2. Evaluation of Inverter Efficiency

To evaluate the efficiency of the inverters with the power modules, the power modules were integrated into inverter on the torque-controlled side (U2). During the test phase, only inverter U2 was used for the efficiency measurement. Meanwhile, inverter U1 on the speed-controlled side was equipped with an integrated IGBT module to function as a load.

The system was evaluated in two operational modes: motor mode and generator mode. At a direct current (DC) voltage of 325 V, the performance characteristics were evaluated across a speed range of 6000 rpm and a torque range of ±250 Nm. These operating parameters are typical for this type of motor.

To ensure the precision of the measurements, the specific points highlighted in red in Figure 5 were approached three times. The data collected during these trials were meticulously recorded and logged using the measurement system, enabling an accurate average calculation for each point. The measurements were systematically collected in both the constant torque region (up to 3000 rpm) and the field weakening region (up to 5500 rpm). The software used could capture a range of data, including currents, voltages, power, and frequencies, from both the energy source and the inverter. Additional parameters, including the motor's speed, torque, power, and frequency, were also documented.

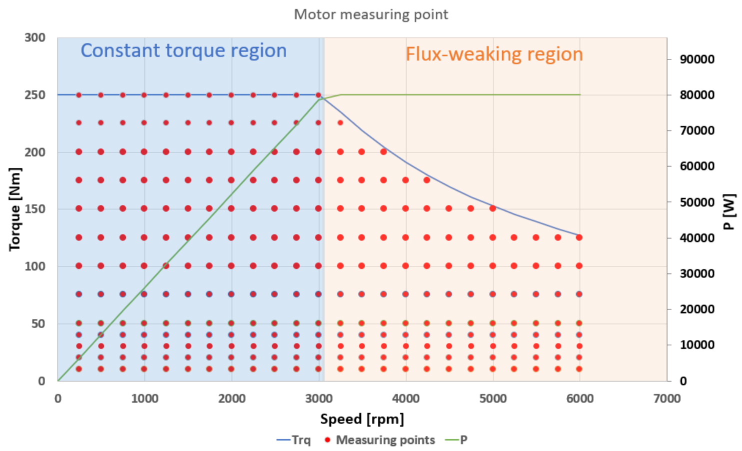


Figure 5 Values of the generated torque and speed, and the corresponding power, at 325VDC

The measuring system includes an automatic calculation of efficiency using the standard formula:

$$\eta = \frac{P_{out}}{P_{in}}$$

The measured values were exported to MATLAB for evaluation and to plot the efficiency maps.

First, an efficiency measurement was conducted using a Si-SiC Fusion power module inverter. To analyze the results fairly and comprehensively, further efficiency measurements were conducted using a Si-IGBT power module and a SiC-MOSFET power module. The same test bench, inverter, and measuring points were used for all measurements. All power modules were designed for 750 V applications, enabling a fair and precise comparison between these technologies.

III. 3. Efficiency Analysis of the Si/SiC Fusion Inverter

The efficiency measurements were conducted by incorporating the HybridPACK™ Drive G2 Fusion power module with Si/SiC trench technology in the inverter test bench. This power module is designed for the 750 V voltage class. The efficiency measurements were performed according to the criteria outlined in Chapter III.2. Based on these measurements, an efficiency map was generated using MATLAB (see Figure 6).

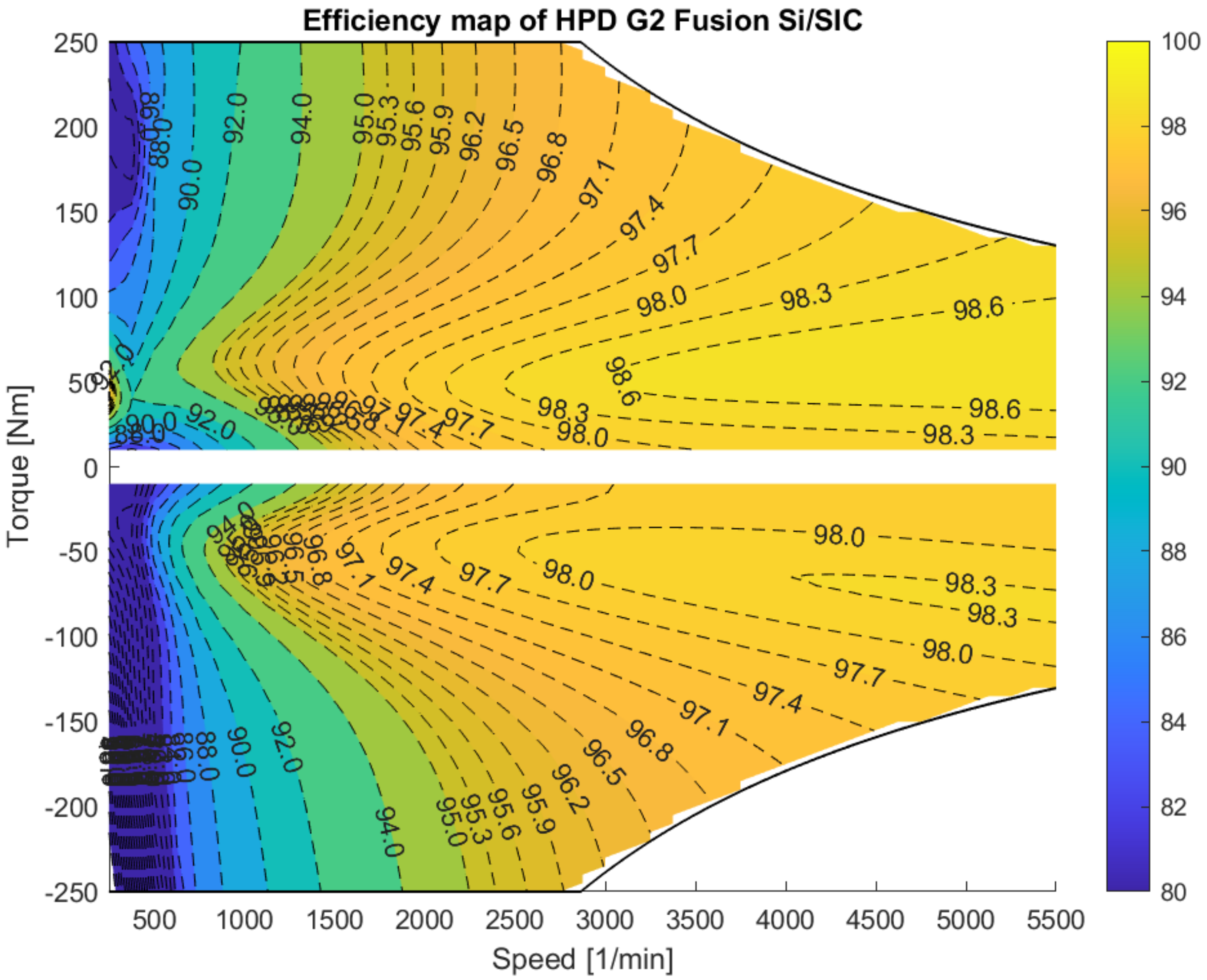


Figure 6 Efficiency map of the HybridPACK™ Drive G2 Si/SiC Fusion power module

The efficiency map is a classic representation where the x-axis denotes speed and the y-axis represents torque. The upper half of the map corresponds to measurements in the motor region, while the lower half pertains to the generator region. The color gradient transitions from dark to light, indicating a shift from low to high efficiency.

During the analysis, the constant torque region up to 3000 rpm was first considered. While efficiency in this region is generally lower due to higher torques at lower speeds, which increase losses, a high efficiency of 98.4% was observed in the motor region, with 98.1% achieved in the constant torque region.

Next, the flux weakening region up to 5500 rpm was analyzed. This region typically achieves the highest efficiency due to increasing speeds and decreasing torques, leading to reduced losses. The maximum efficiency of 98.8% was achieved in the motor region for the Fusion module, while the generator region reached 98.3%.

To ensure a fair and comprehensive analysis, additional efficiency measurements were conducted with two other types of Infineon’s power modules at the same voltage class, i.e., a SiC MOSFET and an Si IGBT based power modules.

III. 4. Efficiency Analysis of the Si-IGBT Inverter

The same efficiency measurement was conducted using an Si-IGBT power module. The module in question is an FS1150R08 HybridPACK™ Drive G2, designed for 750 V voltage classes. The same measurement set-up as the fusion inverter, with the same test configurations was used. Only the power modules and driver boards were changed. Based on the results, an efficiency map was generated (see Figure 7).

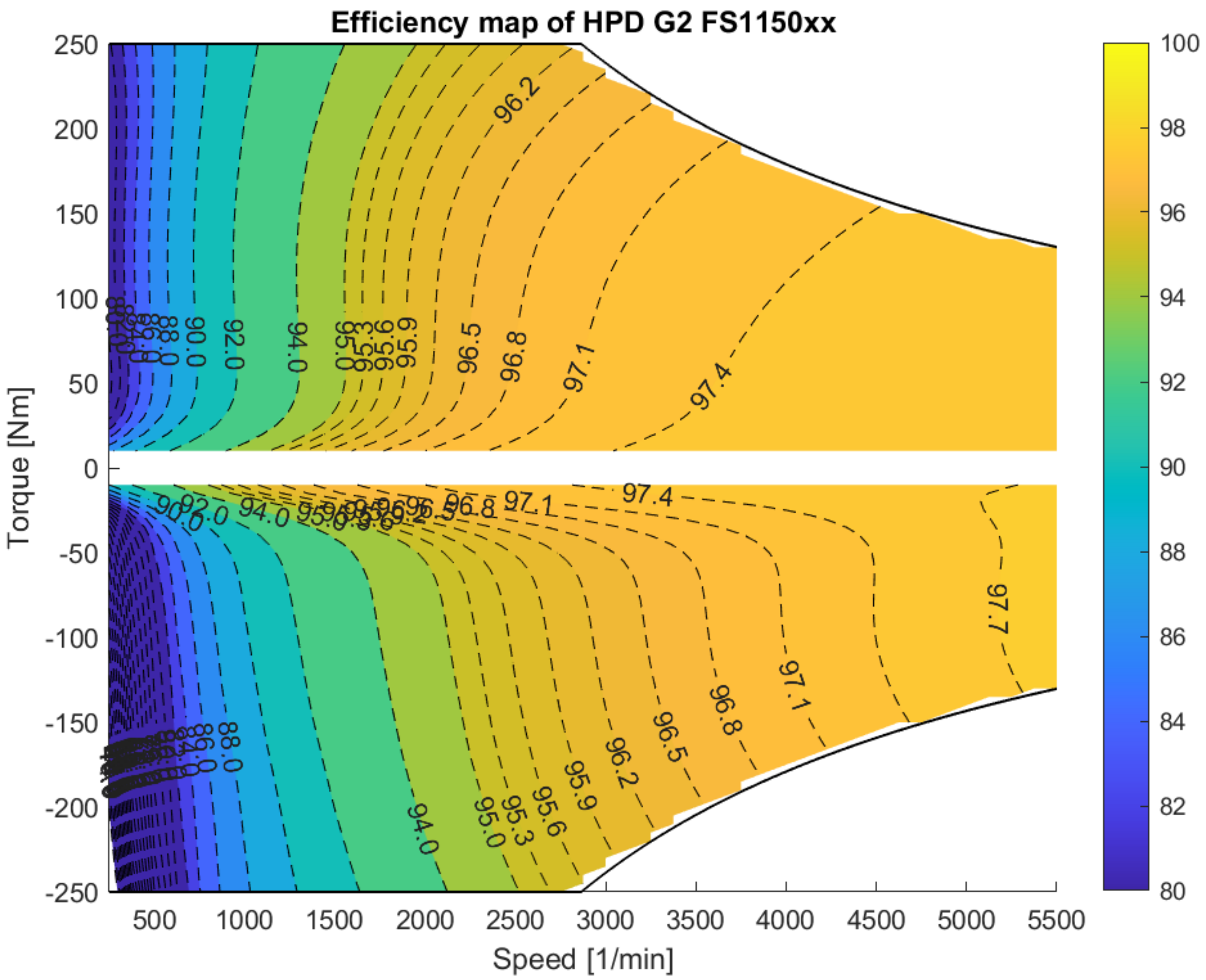


Figure 7 Efficiency map of the HybridPACK™ Drive G2 Si IGBT power module

Initially, the constant-torque region was analyzed. In this region, a maximum efficiency of 97.4% was observed in the generator region, and 97.3% in the motor region. Improvements were identified in the flux-weakening region, with a maximum efficiency of 97.8% in the generator region and 97.6% in the motor region.

The efficiency measurement results were then compared with those of the fusion setup. It is evident that the fusion system, even with a SiC chip content of only 30%, exhibits higher efficiency as can be seen from Table 2. From these results we can see that, in the constant-torque region, the fusion system shows an efficiency improvement of 1.1% in the motor region and 0.7% in the generator region compared to the Si-IGBT module. Similarly, in the flux-weakening region, the fusion system shows an improved performance in terms of efficiency compared to the Si-IGBT system with an efficiency increase of up to 1.2% in the motor region and 0.5% in the generator region.

Table 2. Maximum inverter efficiency in motor & generator mode (Si/SiC Fusion & Si IGBT)

Motorized: Rpm/Eff.	**Si-IGBT Power Module**	**Si/SiC Fusion Power Module**	**Improvement**
>3000 rpm	97,3 %	98,4 %	+ 1,1 %
>6000 rpm	97,6 %	98,8 %	+ 1,2 %

Generative: Rpm/Eff.	Si-IGBT Power Module	Si/SiC Fusion Power Module	Improvement
>3000 rpm	97,4 %	98,1 %	+ 0,7%
>6000 rpm	97,8 %	98,3 %	+ 0,5%

Subsequently, efficiency measurements were performed using a SiC-MOSFET to analyze the differences between these technologies.

III. 5. Efficiency Comparison of Si-IGBT, Si/SiC Fusion, and SiC-MOSFET Inverter

A final efficiency measurement was conducted using the SiC-MOSFET FS01MR08A8 power module also from the 750 V voltage class, HybridPACK™ Drive G2 product family. The test conditions were identical to those of the two previous measurements. An efficiency map was generated, and the maximum efficiencies in both the Constant-Torque and Flux-Weakening regions were analyzed (see Figure 8).

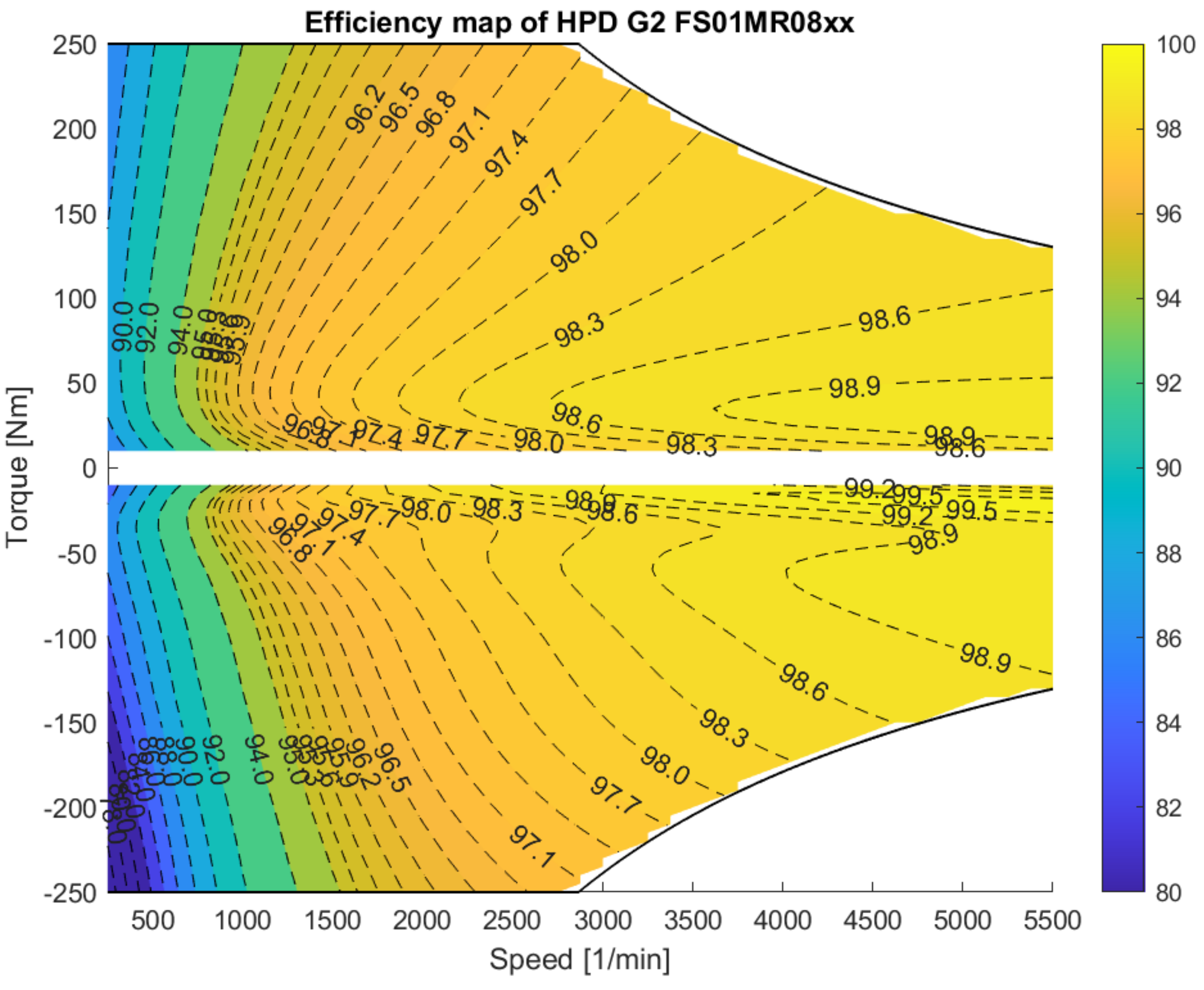


Figure 8 Efficiency map of the HybridPACK™ Drive G2 SiC MOSFET power module

In the Constant-Torque region, the SiC-MOSFET achieved its highest efficiency of 99.1% in generator mode and 98.6% in motor mode. In the Flux-Weakening region, the SiC-MOSFET inverter demonstrated its highest efficiencies, reaching 99.6% in generator mode and 99.1% in motor mode. These results were then compared to those of the Si/SiC fusion (see Table 3).

Table 3. Maximum inverter efficiency in motor & generator mode (Si/SiC Fusion & SiC MOSFET)

Motorized: Rpm/Eff.	Si/SiC Fusion Power Module	SiC-MOSFET Power Module	Improvement
>3000 rpm	98,4 %	98,6 %	+ 0,2 %
>6000 rpm	98,1 %	99,1 %	+ 1 %

Generative: Rpm/Eff.	Si/SiC Fusion Power Module	SiC-MOSFET Power Module	Improvement
>3000 rpm	98,8 %	99,1 %	+ 0,3 %
>6000 rpm	98,3 %	99,6 %	+ 1,3 %

The comparison reveals that the SiC-MOSFET inverter attained the highest efficiencies among the three technologies, primarily due to its high SiC content. In the Constant-Torque region, the SiC-MOSFET showed an improvement of 0.2% in motor mode and up to 1% in generator mode compared to the Si/SiC fusion. A similar trend was observed in the Flux-Weakening region, with an improvement of approximately 0.3% in motor operation and up to 1.3% in generator operation.

These results align with our expectations prior to the measurements. The Si/SiC fusion, which integrates both technologies, positions itself efficiency-wise between IGBT and MOSFET. A comparison of the maximum efficiencies showed that the SiC fusion module offered a 1% improvement over IGBT, while the SiC module demonstrated an enhancement of up to 1.8%. Notably, despite the Si/SiC fusion having a low SiC content of 30%, its efficiency was closer to that of SiC than IGBT (see Figure 9).

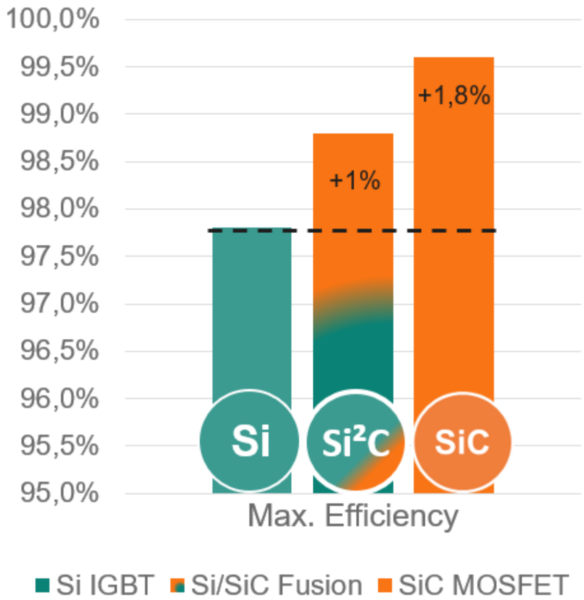


Figure 9 Comparison of the maximum efficiency between IGBT, MOSFET, and Si/SiC Fusion

To better position these results, the efficiency vs. the speed curve was plotted in Figure 10. From this figure we can see that the Si/SiC fusion is placed between SiC MOSFET and Si IGBT across all examined parameters. Furthermore, it is evident that efficiency is influenced by speed and torque. At higher speeds, lower torque is achieved in the flux-weakening range, resulting in reduced losses and consequently increased efficiency.

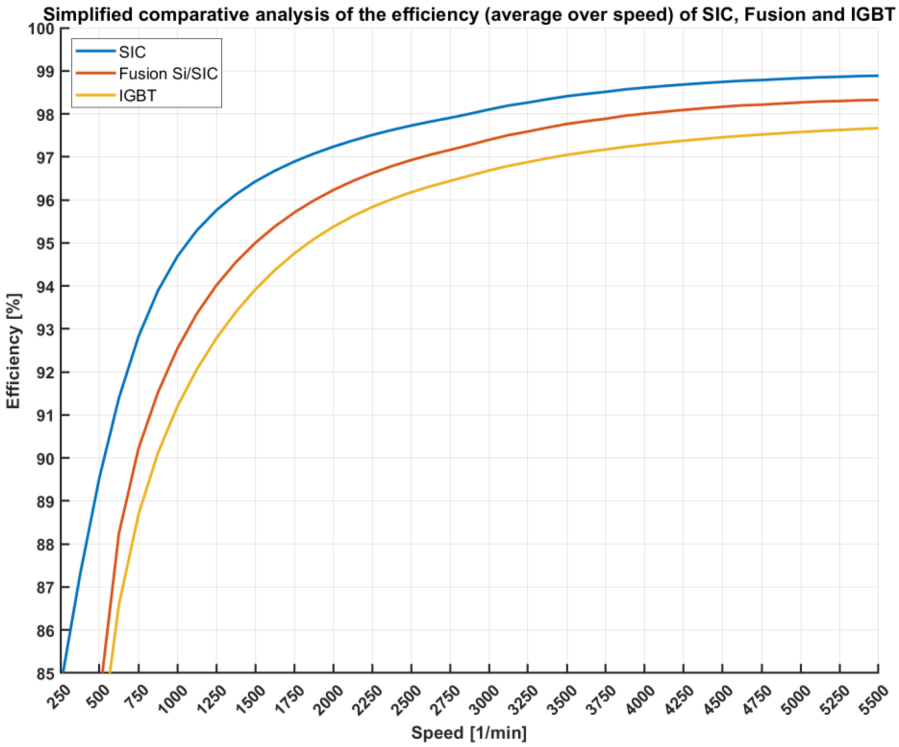


Figure 10: Simplified comparative analysis of the efficiency (average over speed)

The maximum efficiencies achieved are summarized in Table 4, all of which were obtained under conditions of increased speeds and low torque values:

Table 4. Maximum inverter efficiency (Si IGBT, Si/SiC Fusion & SiC MOSFET)

Technology	Maximum efficiency	Speed	Torque
Si IGBT	97,8 %	5500 rpm	-80 Nm
Si/SiC Fusion	99,8 %	5500 rpm	60 Nm
SiC MOSFET	99,6 %	5375 rpm	-20 Nm

IV. Simulation under real WLTP application conditions

The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is a globally recognized standardized test procedure in the automotive industry, primarily used for assessing vehicle performance. This test consists of a series of dynamic driving segments, including acceleration, deceleration, and power application, all within a 30-minute duration, covering a distance of 23.3 kilometers. While there is ongoing debate about its ability to mirror real-world driving conditions due to varying individual driving styles, the WLTP remains a valuable tool for evaluating vehicle efficiency. It helps manufacturers determine the necessary engine power and assess key vehicle parameters such as weight, aerodynamic drag, and acceleration capabilities [3, 4].

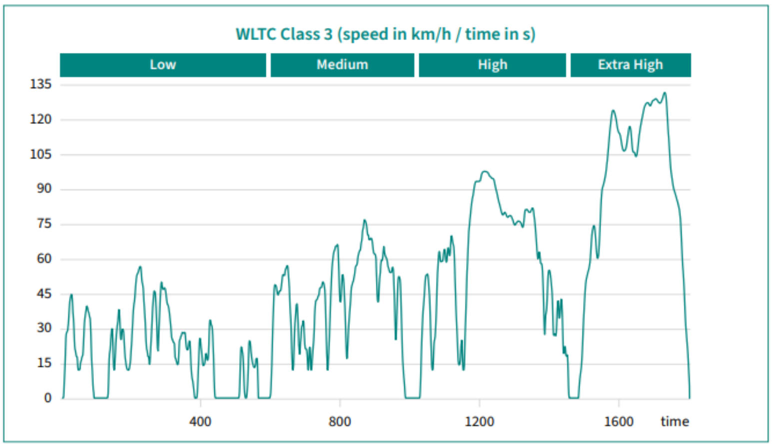


Figure 11 WLTP driving profile

To identify the benefits under real-world application conditions, a WLTP profile was simulated using Infineon's EDT3-IGBT, Si/SiC Fusion, and SiC G2 technology for 400 V systems. The base model used was a 470 V electric vehicle with 175 kW power and a 75-kWh battery, representing a standard SUV. All three technologies were subjected to the same WLTP test conditions in the same vehicle. Overall, the IGBT exhibited a loss of 15.31 kWh, the Fusion technology a loss of 14.88 kWh, and the SiC technology a loss of 14.79 kWh per 100 km, respectively. Considering these results in terms of vehicle range, the base vehicle equipped with IGBT achieved a range of 490 km, while the Fusion technology extended this range to 504 km, representing a 2.9% increase. The SiC technology further improved the range to 507 km, marking a 3.5% enhancement (see Figure 12).

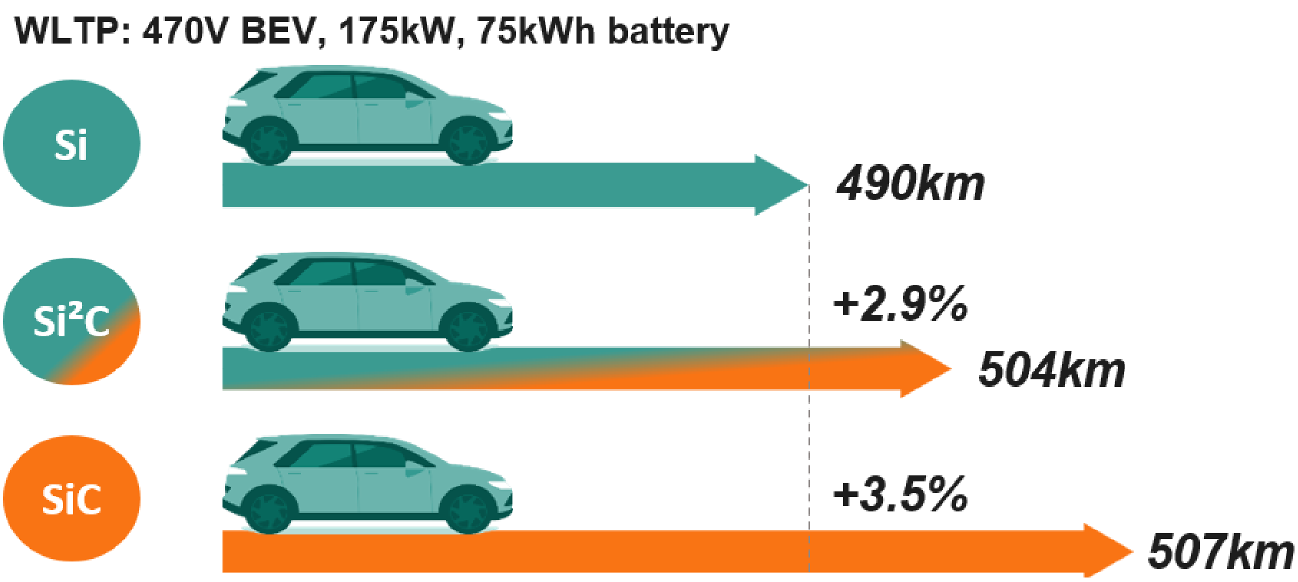


Figure 12 **WLTP comparison**

These findings underscore the significant impact of power module technology selection on vehicle range. However, it is crucial to note that the choice of vehicle also influences the outcome. Selecting a different vehicle would yield varying parameters, such as battery capacity, weight, frontal area, drag coefficient (c_w), and other factors, leading to different results.

Notably, the efficiency comparison showed a maximum difference of 1.2% between IGBT and Fusion technologies. However, under real WLTP conditions, the range increase was significantly more pronounced, with a 2.9% improvement. Equally interesting is how closely the Si/SiC Fusion technology's performance approaches that of SiC, with only a 3 km difference in range.

The reasons behind the superior performance of the Si/SiC Fusion technology under WLTP conditions were discussed in Chapter 2. WLTP primarily involves light-load conditions where SiC technology is predominantly utilized, thereby leveraging its advantages.

V. Conclusions

In conclusion, the study conducted in this paper demonstrated the significant advancements achieved with the Si/SiC Fusion Power Module, particularly in enhancing the efficiency and performance of traction inverters for battery electric vehicles (BEVs). The Infineon HybridPACK™ Drive G2 Fusion module, integrating 30% SiC and 70% Si components, achieved exceptional efficiency, reaching over 98.8% under various operating conditions. This hybrid approach successfully balances the cost-effectiveness of Si IGBTs with the superior efficiency of SiC MOSFETs, offering a compelling solution for the automotive industry. The Fusion module outperformed the traditional Si IGBT module, with efficiency improvements of up to 1.2% in the constant torque region and 1.5% in the flux-weakening region. Although slightly less efficient than the full SiC module, the Fusion technology closely approaches its performance, making it a more accessible option for widespread adoption. Under real-world conditions simulated through the WLTP cycle, the Fusion module demonstrated a 2.9% increase in vehicle range compared with Si IGBTs, achieving 504 km versus 490 km for the base vehicle. This improvement underscores the practical benefits of the Fusion technology in enhancing EV performance and efficiency. The study highlights the importance of the Fusion module's cost-performance balance, making BEVs more viable and accessible. This technology not only supports current automotive advancements but also paves the way for future developments in power electronics, contributing to the broader adoption of sustainable transportation solutions.

References

[1] Gorte, N., Akabay, H., & Pannemann, C. (2025). "An evaluation of the performance and efficiency of a Si/SiC fusion power module based inverter ". *Proceedings of PCIM Europe 2025, Nürnberg, Germany (in press).*

[2] Ippisch, M., Reiter, T., Niendorf, M., Jakobi, W., & Unzer, M. (2024). "Maximizing cost-efficiency in electric drivetrains: A SiC/Si fusion switch approach ". *Proceedings of PCIM Europe 2024. Nürnberg, Germany*. doi.org/10.30420/566262369

[3] Reiter, T., & Ippisch, M. (2024). "Fusion switch concept addresses the cost-performance dilemma in EV powertrains". *In PCIM Asia 2024. Shenzhen, China*. doi.org/10.30420/566414053

[4] Akabay, H., Gorte, N., Ezzeddine, K., Pannemann, C., & Thoben, M. (2024). "The characterization of a silicon-carbide Gen2 based inverter on a motor testbench". *Proceedings of EEHE 2024*. *Bamberg, Germany*. eehe.de/wp-content/uploads/Final_The-Characterization-of-a-Silicon-Carbide-Gen2-based-Inverter-on-a-Motor-Testbench_revised.pdf